

Di-jet asymmetric momentum transported by QGP fluid

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Abstract

We study the collective flow of the QGP-fluid which transports the energy and momentum deposited from jets. Simulations of the propagation of jets together with expansion of the QGP-fluid are performed by solving relativistic hydrodynamic equations numerically in the fully $(3 + 1)$ -dimensional space. Mach cones are induced by the energy-momentum deposition from jets and extended by the expansion of the QGP. As a result, low- p_T particles are enhanced at large angles from the jet axis. This provides an intimate link between the observables in di-jet asymmetric events in heavy ion collisions and theoretical pictures of the medium excitation by jet-energy deposition.

Keywords: QGP, jet quenching, relativistic hydrodynamics, Mach cone

1. Introduction

In heavy-ion collisions at Relativistic Heavy Ion Collider (RHIC) in BNL and Large Hadron Collider (LHC) in CERN, the deconfined phase of quarks and gluons, namely the quark-gluon plasma (QGP) is supposed to be realized experimentally. The expansion of the QGP is well described by relativistic hydrodynamics [1–5]. At the same time as the QGP, large- p_T partons, so-called jets, are produced through the initial hard scattering between the partons inside colliding nuclei and penetrate the QGP. Due to the strong coupling with the QGP-medium, these jet particles travel losing their energy. At the leading order, the jet particles are created as a back-to-back pair with the same energy owing to the energy-momentum conservation law. Depending on the relation between the geometry of the medium and the position of the pair creation, the amount of the energy loss differs between the jet partons. At the LHC, events such that the transverse momentum of jets are highly-asymmetric are observed and these experimental facts are consistent with jet quenching picture [6, 7]. Furthermore, according to the data from the CMS Collaboration, this imbalance of dijet- p_T is compensated by low- p_T particles at large angles from the jet axis and the total- p_T of the entire system is well balanced [7]. It can be supposed that these low- p_T particles are originating from a medium wake induced by the energy and momentum deposited from jets.

Here, we perform simulations of dijet asymmetric events to study the transport process of energy and momentum deposited from jet particles in the expanding QGP medium. To describe the medium response to the energy-momentum deposition, we solve relativistic hydrodynamic equations with source terms in the fully $(3+1)$ -dimensional coordinate system numerically. Then, we investigate the transverse-momentum balance in dijet events and show that low- p_T particles at large angles from the jet axis play a crucial role in the transverse-momentum balance.

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2. Model and Simulations

Assuming local thermal equilibrium of the QGP, we solve relativistic hydrodynamic equations, to describe the space-time evolution of the QGP. Here, source terms, which are the 4-momentum density deposited from the traversing jet partons, are introduced in the hydrodynamic equations.

$$\partial_\mu T^{\mu\nu}(x) = J^\nu(x), \quad (1)$$

where $T^{\mu\nu}$ and J^ν are the energy-momentum tensor of the QGP-fluid and the source terms, respectively. The energy-momentum tensor for perfect fluids can be decomposed using the 4-flow velocity $u^\mu = \gamma(1, \mathbf{v})$ as

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}. \quad (2)$$

Here ϵ is the energy density, P is the pressure and $g^{\mu\nu} = \text{diag}(1, -1, -1, -1)$ is the Minkowski metric. As an equation of state, the ideal gas equation of state for massless partons is employed here: $P(\epsilon) = \epsilon/3$. We assume that the deposited energy and momentum are immediately equilibrated. The source terms for a massless particle traveling through the fluid are given by

$$J^\mu = -\frac{dp_{\text{jet}}^0}{dt} \frac{p_{\text{jet}}^\mu}{p_{\text{jet}}^0} \delta^{(3)}(\mathbf{x} - \mathbf{x}_{\text{jet}}(t)). \quad (3)$$

For dp_{jet}^0/dt , the collisional energy loss is used [8]. Here we multiply the energy loss by a constant, whose value is fixed throughout all simulations, to simulate large asymmetric dijet events such as observed at the LHC. We solve the equations (1) numerically without linearization in the $(3+1)$ -dimensional Milne coordinates (τ, x, y, η_s) . This framework enables us to simulate the collective flow induced by jet particles on an expanding medium. Through the Cooper-Frye formula, we calculate the momentum distribution of particles from hydrodynamic outputs $T(x)$, $u^\mu(x)$ [9].

We set up the initial profile of the QGP-fluid at $\tau_0 = 0.6 \text{ fm}/c$. The initial energy density in the η_s -direction is flat like the Bjorken scaling solution in the mid-rapidity region $|\eta_s| < 10$. The flat region is smoothly connected to the vacuum at both ends by a half Gaussian with the width $\sigma_\eta = 0.5$ [10, 11]. For the initial transverse profile, we use the smooth energy density for central Pb-Pb collisions obtained from the MC-Glauber model [12]. The initial value of energy density at origin is $e(\tau_0, \mathbf{x} = 0) = 100 \text{ GeV}/\text{fm}^3$. A back-to-back pair of massless partons is supposed to be produced at $(\tau = 0, x = x_0, y = 0, \eta_s = 0)$ with the same energy, $p_{\text{jet}}^0(\tau = 0) = 200 \text{ GeV}$. These partons always travel along the x -axis at the speed of light and start to interact with the expanding medium at $\tau = \tau_0$. To characterize the p_T -imbalance between the pair of the partons, the asymmetry ratio is introduced.

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad (4)$$

where $p_{T,1}$ and $p_{T,2}$ are transverse momenta of the energetic partons at the freeze-out ($p_{T,1} > p_{T,2}$). The value of A_J can be controlled by moving the position of pair creation x_0 .

3. Results

The energy density distribution of the QGP fluid at $\tau = 9.6 \text{ fm}/c$ is shown in Figure 1. The pair of the energetic partons is produced at $x_0 = 1.5 \text{ fm}$ in this case. One sees oval structures of higher energy density, which are Mach cones [13, 14] distorted by the radial flow of the fluid, in the transverse plane at $\eta_s = 0$ (Fig. 1 (a)). In the reaction plane $y = 0$ (Fig. 1 (b)) Mach cone-like structures are also seen. Though they do not develop so much apparently because the Milne coordinate itself expands in the longitudinal direction.

To see the total p_T -balance of the entire system, total- p_T along the jet axis is defined as

$$\langle p_T^\parallel \rangle = \langle \sum_i -p_T^i \cos(\phi_i - \phi_1) \rangle, \quad (5)$$

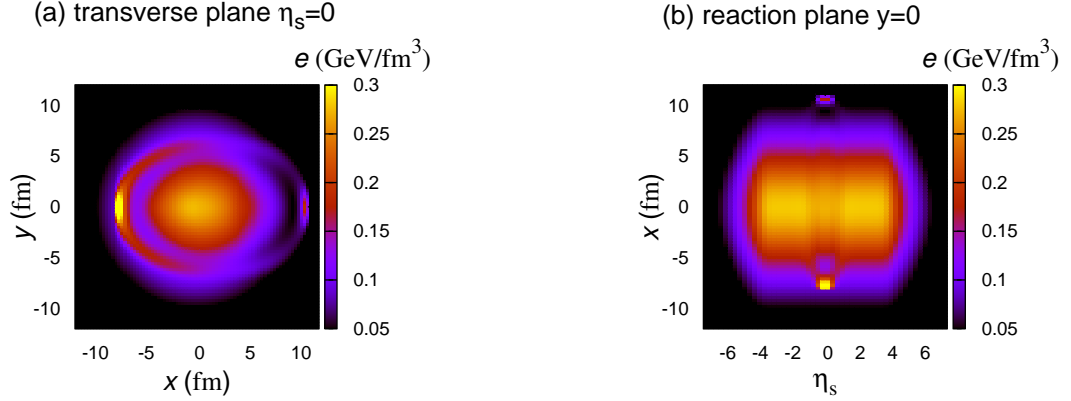


Figure 1. (Colour Online) Energy density distribution of the QGP-fluid at $\tau = 0.6$ fm/c in the transverse plane at $\eta_s = 0$ (a) and in the reaction plane at $y = 0$ (b). The pair-production position of the energetic partons is $(\tau = 0, x = 1.5 \text{ fm}, y = 0, \eta_s = 0)$. The energetic partons travel in the opposite direction along the x -axis at the speed of light.

where the sum is taken over all particles in the entire system, and their p_T is projected onto the sub-leading jet axis $\phi_2 = \phi_1 + \pi$ in the transverse plane. We calculate the contribution to $\langle p_T^\parallel \rangle$ from the fluid through the Cooper-Frye formula [9]. We assume that the freeze-out occurs at fixed proper time $\tau_f = 9.6$ fm/c, which is typical for central Pb-Pb collisions at the LHC energy. By adding the contribution from the jet particles to the contribution from the fluid, we obtain $\langle p_T^\parallel \rangle$. Figure 2 shows $\langle p_T^\parallel \rangle$ as a function of A_J . Here, we consider 2-jet cones of the size $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.8$ around the axes of the energetic partons. Figures 2 (a), (b) and (c) show the results for overall, in-cone and out-of-cone, respectively. Each coloured histogram corresponds to the contribution from a p_T -region of the particles. The solid black circles show the contribution from the whole particles. In the in-cone region, the contribution from high- p_T particles are dominant and negative. On the other hand, there is only the positive contribution from particles of $p_T < 2$ GeV/c in the out-of-cone region. These contributions from the in-cone region and from the out-of-cone region are balanced due to the energy-momentum conservation of the entire system. The low- p_T particles in the out-of-cone region are originated from the deposited energy and momentum transported by the collective flow in the QGP-fluid.

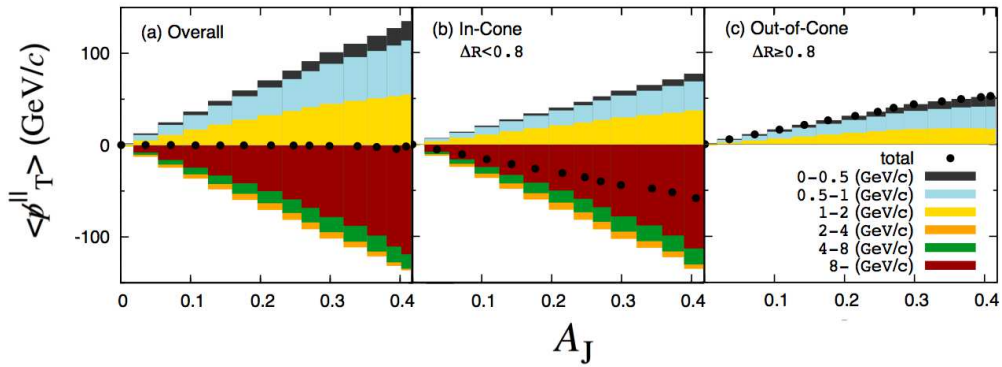


Figure 2. (Colour Online) Total- p_T along the jet axis. $\langle p_T^\parallel \rangle$ is shown as a function of A_J for the whole region (a), for inside ($\Delta R < 0.8$) jet cones (b) and for outside ($\Delta R \geq 0.8$) jet cones (c). The solid black circles indicate the contribution to $\langle p_T^\parallel \rangle$ from the particles in the whole p_T region. Each coloured histogram corresponds to the contribution from the particles in six transverse momentum ranges: 0-0.5, 0.5-1, 1-2, 2-4, 4-8 GeV/c, and $p_T > 8$ GeV/c.

4. Summary

We reported that low- p_T particles are enhanced at large angles from the jet axes as a result of the transport of the energy and momentum deposited from jets in the expanding QGP medium. We performed simulations of asymmetric dijet events in Pb-Pb collisions at the LHC. To describe the collective flow induced by the energy-momentum deposition, we solved relativistic hydrodynamic equations with source terms numerically in the fully $(3 + 1)$ -dimensional space. Mach cones are excited by the energy deposited from jets and then distorted by the expansion of the background medium. We also found that low- p_T particles are enhanced at large angles from the jet axes and compensate a large fraction of the transverse momentum deposited from jets. This low- p_T enhancement at large angles is caused by transport of the deposited energy and momentum by the collective flow in the QGP-fluid. This study suggests an intimate link between the data from CMS and medium response to energy-momentum deposition of jets.

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References

- [1] U. W. Heinz and P. F. Kolb, Nucl. Phys. A **702** (2002) 269.
- [2] T. D. Lee, Nucl. Phys. A **750** (2005) 1.
- [3] M. Gyulassy and L. McLerran, Nucl. Phys. A **750** (2005) 30.
- [4] E. V. Shuryak, Nucl. Phys. A **750** (2005) 64.
- [5] T. Hirano and M. Gyulassy, Nucl. Phys. A **769** (2006) 71.
- [6] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **105** (2010) 252303.
- [7] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. C **84** (2011) 024906.
- [8] M. H. Thoma, Phys. Lett. B **273** (1991) 128.
- [9] F. Cooper and G. Frye, Phys. Rev. D **10** (1974) 186.
- [10] J. D. Bjorken, Phys. Rev. D **27** (1983) 140.
- [11] B. Schenke, S. Jeon and C. Gale, Phys. Lett. B **702** (2011) 59.
- [12] T. Hirano, P. Huovinen and Y. Nara, Phys. Rev. C **84** (2011) 011901.
- [13] H. Stoecker, Nucl. Phys. A **750** (2005) 121.
- [14] J. Casalderrey-Solana, E. V. Shuryak and D. Teaney, J. Phys. Conf. Ser. **27** (2005) 22.